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Impact of legislation on olive mill wastewater management: Jordan as a case study

Maha Halalsheh[a], Ghada Kassab[b] and Khaldoun Shatanawi[b]

[a]*Corresponding author. Water, Energy and Environment Center, The University of Jordan, 11942 Amman, Jordan.*
E-mail: halalshe@ju.edu.jo
[b]*Civil Engineering Department, School of Engineering, The University of Jordan, 11942 Amman, Jordan*

Abstract

Olive mill wastewater (OMWW) management is becoming more challenging and a major environmental concern due to several factors including the very complex wastewater, which is considered one of the most difficult to treat. Seasonal production and small scattered family milling businesses have resulted in augmented management challenges. As the eighth largest olive oil exporter, Jordan is not an exception and faces some environmental and management concerns. The country had recently managed OMWW well; however, some issues need to be addressed in order to meet environmental requirements of the growing business. This paper aims at evaluating the Jordanian experience in OMWW management and recommends additional alternatives. OMWW shipping is controlled by a tracking system to designated disposal sites. However, weak enforcement of penalties results in violations. Moreover, current management practical options are limited in view of existing regulations since agricultural land application and decentralized management are discouraged. Legislative gaps are discussed and suggestions for a comprehensive revision established to allow for additional management alternatives. A revised legislative framework that takes into account resource recovery and the valorization of OMWW based on scientific evidence is highly recommended.

Keywords: Legislation; Management; Olive mill wastewater; Treatment cost; Treatment technologies

Highlights

- OMWW is one of the most complex and difficult to treat wastewaters.
- Technological advances for OMWW treatment exist, however, costs are still the most limiting factor in the scale up.
- Controlled land application shall be considered for OMWW in Jordan.
- Modifying legislations is critical to improve OMWW management in Jordan.

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Introduction

The origin of domesticated olive trees was believed to be the Jordan Valley where olive stones have been traced back to the Chalcolithic in the 6th millennium BP (Zohary & Spiegel-Roy, 1975). However, recent observations showed that olive tree cultivation had originated in the northern Levant and spread afterwards across the Mediterranean basin (Besnard *et al.*, 2013). At present, olive tree products are increasing and include mainly olive oil, preserved olive fruits, canned olive fruits, olive leaf tea, medicine, health products, and food and industrial raw materials. Olive oil was discovered accidentally (Kapellakis *et al.*, 2008), whereas olive oil extraction using stone mortars and presses had accompanied the expansion of olive tree cultivation since 5000 BC (Kaniewski *et al.*, 2012; Di Giovacchino, 2013). Mechanical extraction of olive oil was only advanced during the 1900s after the development of percolation and centrifugation systems (Di Giovacchino, 2013). Currently, and according to the International Olive Oil Council (2019), European Union countries produce 68% of global olive oil, while the main 15 olive oil producing countries produce 96% of the total quantity. The main olive oil producing countries are shown in Figure 1 and can be arranged in descending order as the following: Spain, Italy, Greece, Tunisia, Turkey, Morocco, Portugal, Syria, Algeria, Egypt, Argentina, Jordan, Palestine, Lebanon and Israel. It is noteworthy that olive oil production has increased worldwide since 2005 by 40%, indicating increased global demand (Dermeche *et al.*, 2013; Aggoun *et al.*, 2016) due to excellent oil characteristics and known health benefits. It is estimated that the global olive oil market size will grow at a compound annual growth rate of 3% during the period 2020–2023 (Market Reports World, 2020). It is also worth noting that China began to plant olives in the 1960s in the southwest and currently the speed of this market's development is faster than many other regions in the world (Cheng *et al.*, 2017, as cited in Wang *et al.*, 2019). Olive cultivation is also expanding in Middle East countries, the USA, Argentina, and Australia (Paraskeva & Diamadopoulos, 2006).

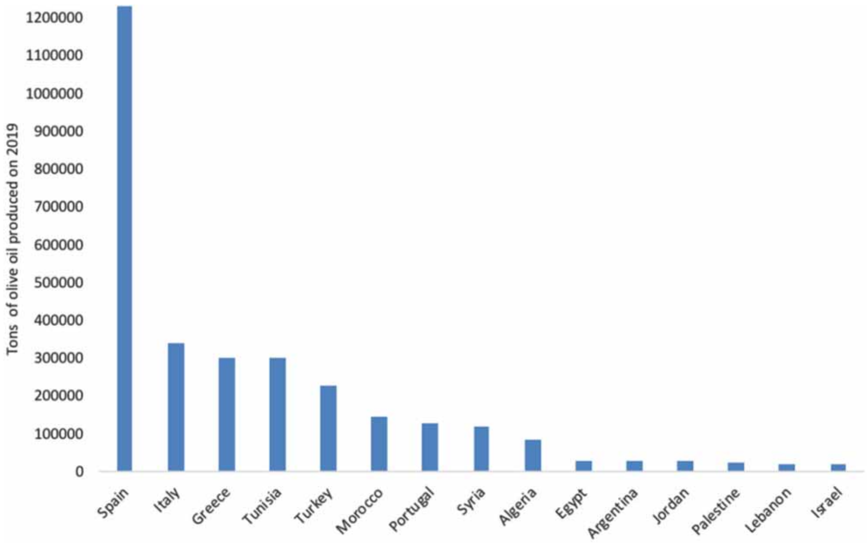

Fig. 1. Tons of olive oil produced by main olive oil producing countries (International Olive Oil Council, 2019).

In Jordan, the olive industry had enlarged significantly during the last years. Olive trees cover 77% of the tree-planted area and account for 24% of the total cultivated area. Annual production of olive fruits had increased to 212,456 tons in 2018 (Ministry of Agriculture, 2018) as compared to 167,794 tons in 2007 (Ministry of Agriculture, 2007). Almost 80% of olives are utilized for olive oil production and the country is considered the eighth largest exporter of olive oil (ILO, 2014, as cited in Al-Hiary *et al.*, 2019). Jordan has 128 olive mills (ISSP-USAID, 2013), with almost 70% of the mills located in the northern regions, while 22 and 8% are located in the middle and southern governorates, respectively. Different oil-extraction techniques exist and affect the quality of the produced olive oil, particularly its physicochemical and organoleptic characteristics. According to the Jordan Ministry of Agriculture, 7% of the mills use traditional pressing techniques, whereas the rest uses modern pressing techniques (data 2012–2013).

The main by-product of the oil extraction process is olive mill wastewater (OMWW), which was historically discharged directly onto land, as revealed by many discovered pits containing layers of blackened soil and located at the outlet of Cyprian olive presses (Hadjisavvas, cited in Kapellakis *et al.*, 2008). Recently, the annual generation of OMWW in the Mediterranean was estimated to be 30 million cubic meters (Chiavola *et al.*, 2014), and is becoming a major environmental concern aggravated by the increase in olive oil production and technological developments. For instance, the conversion of traditional pressure olive mills into centrifugal olive mills produced higher amounts of wastewater (Capra *et al.*, 2010). Besides the increase in quantities, OMWW is considered one of the most difficult-to-treat effluents (Sarris *et al.*, 2011; Zagklis *et al.*, 2013; Pulido, 2016). This wastewater is characterized by its high content of organic matter ranging from 4 to 15% (Bargougui *et al.*, 2019). In addition, OMWW is acidic and exhibits high concentrations of polyphenolic compounds, which are known to be the major causes of the high phytotoxicity and poor biodegradability of OMWW (Aliakbarian *et al.*, 2015; Meftah *et al.*, 2019). Different methods have been suggested to remove phenolic compounds before any recommended conventional biological treatment. For instance, advanced oxidation processes (Kilic *et al.*, 2019), ultrasonic extraction (Klen & Vodopivec, 2011), physicochemical methods such as membrane filtration (Sygouni *et al.*, 2019), and some biological techniques (Rahmanian *et al.*, 2014) were suggested for removal of phenolic compounds. Although OMWW treatment could be thereabouts achieved technologically, it is still far beyond being solved realistically, mainly due to economic reasons. The small scale and dispersed nature of the olive mills and the seasonality of the process coupled with OMWW complex characteristics has hindered the application of economic feasible treatment solutions (Pulido *et al.*, 2017). At the same time, affordable treatment solutions have not yielded the required effluent quality to meet stringent environmental standards. Accordingly, olive oil producing countries have adopted different management alternatives responding to enforced regulations. Literature describing OMWW management in EU countries is abundant (Kapellakis *et al.*, 2006; Inglezakis *et al.*, 2012; Kelessidis & Christoforou, 2014; Koutsos *et al.*, 2018); however, there is hardly any literature reporting and assessing existing management practices in Jordan. In this regard, challenges associated with OMWW management in the country can be divided into two main themes: first, illegal discharges of OMWW to municipal sewer systems are still performed and result in malfunctioning of wastewater treatment plants operated by the Water Authority of Jordan. Moreover, illegal discharge of OMWW to the environment is creating an additional challenge to the Ministry of Environment; secondly, challenges related to the management of existing disposal sites that lack resources. National discourse had been initiated viewing better management alternatives and included OMWW transportation, treatment, and final disposal. Some voices called for decentralized wastewater treatment and valorization using good examples existing in other olive oil producing countries. Other voices called for keeping centralized solutions and for improving the conditions of existing disposal sites while exerting better control on OMWW shipping. Therefore, the present work aims at evaluating the current Jordanian experience in OMWW management in view of the existing regulations, and presenting foreseen alternatives that might address the existing challenges.

Methodology

Semi-structured interviews were conducted with Assistant Secretary General of the Jordan Ministry of Environment for Technical Affairs, Assistant Secretary General of the Jordan Water Authority for Laboratory and Quality Affairs, and Vice chair of the Jordan olive mills owners' union. Interviews were oriented to discuss the progress that has been made in the current management protocol, and challenges faced in enforcement of existing legislation. Moreover, a roundtable discussion was organized in order to further discuss bottlenecks related to illegal discharges of OMWW in the sewerage system, existing regulations, and management of OMWW disposal sites. First, a stakeholders' analysis was conducted to identify, prioritize, and determine key stakeholders involved in OMWW management. This exercise was conducted by a group of experts at the University of Jordan and professionals at the Jordan Engineers Association. Second, officials representing key stakeholders were invited to a roundtable discussion at the Water, Energy and Environment Center at the University of Jordan. Invited key stakeholders represented the Ministry of Environment, Ministry of Local Administration, Royal Administration of Environment Protection, Jordan Olive Products Exporters Association, Olive Mills Owners Union, Ministry of Agriculture, and Water Authority of Jordan. The roundtable discussion was organized jointly by the University of Jordan and the Jordan Engineers Association. As a preparation for the roundtable discussion, current Jordanian legislation regulating OMWW management options was reviewed and compared with other legislation in olive oil producing countries (as recently reported in peer-reviewed papers). Moreover, peer-reviewed papers were searched for existing OMWW treatment alternatives and for the associated operation and maintenance costs in order to support decision-making processes regarding future planning of OMWW management.

Bottlenecks related to existing regulations and standards

OMWW characteristics and the enforced law-limits for different discharge purposes are shown in Table 1. The chemical composition of OMWW is highly variable depending on different factors including olive type, tree age, cultivation methods, fruit maturity degree, oil extraction technique, geographical and climatic conditions, and applied fertilizers and pesticides (Yay *et al.*, as cited in Ioannou-Ttofa *et al.*, 2017). Jordan considers OMWW as industrial wastewater that needs to be treated before reuse. In case reuse for agricultural purposes is intended, OMWW has to meet Jordanian standards for industrial wastewater use JS 202/2007, as shown in Table 1. On the other hand, OMWW effluent shall be treated before discharge to the public sewerage system and effluent has to meet instructions for the disposal of non-domestic wastewater to the sanitation system for the year 2017 issued in accordance with Articles 3, 4, 21, and 23 of the sanitation system No. 66 of 1994 (Table 1). Apparently, almost complete removal of COD and phenols are demanded in the case OMWW is either reused for agricultural

Table 1. OMWW characteristics in comparison with enforced standards in Jordan.

Parameter	Reference						Industrial effluent JS 202/ 2007[a]	Industrial effluent JS 202/ 2007[b]	Instructions for disposal of non-domestic ww to sewer system	ELVs for discharges of OMWW to surface water and sewers (in parenthesis)[c]			
	Alkhatib *et al.* (2009)	Azzam *et al.* (2013)	Ayoub *et al.* (2014)	Rusan & Malkawi (2016)	Jaradat *et al.* (2018)	Al-Essa (2018)				Italy	Greece	Spain	Portugal
pH	5.48–5.91	4.6	4.91	4.7	4.7	4.63	6–9	6–9	5.5–9.5	5.5–9.5 (5.5–9.5)	6–9 (6–9.5)	5.5–9.5	6–9
EC/mScm^{-1}		12.71	7.64	7.6	14.9	19.89							
Na/mg			59.7			279.9		230					
Cl/mg			504				350	400					
K/mg			2,782			6,366							
Mg/mg			227					100					
Ca/mg			294					230					
TDS (mg/l)	16,984–80,355	27,000	26,345			34,700	2,000	2,000	2,000				
COD (mg/l)	78,536–160,096	40,000	58,614	118,800	184,700	12,000	150	100	1,500	160 (500)	45–180 (1,000)	160–500	150
BOD_5 (mg/l)	23,248–63,271		36,329				60	30		40 (250)	15–60 (250–500)	40–300	40
TS (mg/l)			69,835										
FOG (mg/l)	2,008–13,118						8	8	100	20 (40)	5–40 (40–100)	20–40	15
Phenols (mg/l)	1,739–4,432		2,269				<0.002	<0.002	5	0.5 (1)	0.005–0.5 (5–10)	0.5–1	0.5
Total N (mg/l)			544	96.8	3,790		70	45	100	15 (30)	10–15 (25)	15–50	15
Nitrate (mg/l)			33			360	80	30		20 (30)	4–50 (20)	10–20	50
Total P (mg/l)			245	1,667	3,200					10 (10)	0.2–10 (10)	10–20	10
Sulfate (mg/l)			100				300	500					
Iron (mg/l)			38				5	5	30				
Zinc (mg/l)			5.8				5	5	10				
Cadmium (mg/l)			<0.005				0.01	0.01	0.5				
Lead (mg/l)			<0.09				0.2	0.2	0.6				

[a] The maximum permissible concentration in reclaimed industrial wastewater that is released for torrents, wadis and water bodies.

[b] Irrigation of cooked vegetables, parks, playgrounds and roadsides within cities.

[c] PROSODOL and Life (2012).

production or discharged into the public sewers' network. COD and phenols have to be reduced in the best conditions from 40,000 mg/l and 1,736 mg/l to 100 mg/l and 0.002 mg/l, respectively, when OMWW is used for irrigation. Moreover, TDS has to be reduced to 2,000 mg/l, which would necessitate the employment of desalination techniques. In effect, any single treatment technology will not have the capacity to achieve such very strict effluent limits. The same would apply when OMWW is to be discharged to the public sewerage network or to water bodies, as can be seen in Table 1. Obviously, the established effluent phenol limit for discharging to water bodies is stricter as compared with those established by EU countries (Table 1). Established limits for COD are 150 mg/l and 100 mg/l when effluents are used for irrigation or discharged to sewerage systems, respectively. Accordingly, and as can be shown from Table 1, many olive oil producing countries discourage OMWW from being discharged to water bodies and public networks. The required level of treatment is far beyond being achievable in view of treatment costs and the complex chemical composition of OMWW. For elaboration, estimated costs of treatment of different technologies together with the obtained treatment efficiencies are shown in Table 2. The most effective treatment option as reported in literature is membrane technology (with appropriate pre-treatment steps), which might achieve 98% removal of both the COD and phenols (Paraskeva *et al.*, 2007). The obtained removal efficiency might not meet the enforced allowable limits even at the very high treatment costs reported at 32 €/m^3 (Paraskeva *et al.*, as cited in Gebreyohannes *et al.*, 2016). Other tested treatment technologies include coagulation-flocculation (Vuppala *et al.*, 2019); electro-coagulation (Neffa *et al.*, 2010; Haksevenler & Alaton, 2014; Abou-Taleb *et al.*, 2018; Jalo *et al.*, 2018); aerobic biological treatment (El-Hajjouji *et al.*, 2014; El-Moussaoui *et al.*, 2018); anaerobic digestion (Gunay & Karadag, 2015; Enaime *et al.*, 2019); electrolysis (Bouhssine *et al.*, 2013); Fenton treatment (Amor *et al.*, 2015); photo-Fenton treatment (Ahmed *et al.*, 2011); and ozonation (Martins *et al.*, 2015). Reported removal efficiencies for the COD and phenols for these systems are generally lower than membrane systems, although less costly. However, none of the presented treatment technologies have the capacity to meet Jordanian effluent quality standards for any reuse option.

OMWW in Jordan is also discouraged from being used for irrigation purposes since the required treatment levels are simply not attainable (Table 1). Instructions for licensing, establishing, and operating olive presses No. 15 of 2018 issued in accordance with the provisions of Article 16 of the Agriculture Law No. 13 of 2015 and its amendments commands OMWW to be shipped to special disposal sites. For comparison, many EU olive oil producing countries allow OMWW agricultural irrigation. It should be noted that no common EU legislation regulating olive mill discharges exists at the moment and, hence, standards are left to individual countries (Koutsos *et al.*, 2018). For instance, two-phase olive mill wastes or olive mill wastewaters in Spain are not generally considered hazardous waste, but rather secondary products that can be valorized (Inglezakis *et al.*, 2012). Correspondingly, Article 7 of Decree 4/2011 of the Regional Government of Andalusia allows conditional OMWW agricultural land application at a rate not exceeding 50 m^3 ha^{-1} yr^{-1} (Doula *et al.*, 2017). Italy permits annual land application of OMWW up to 50 and 80 m^3 ha^{-1} yr^{-1} for press and centrifugal milling systems, respectively (Laor *et al.*, 2011; Vella *et al.*, 2016). In fact, according to Italian Law No. 574/1996, vegetation waters derived from oil milling can be used for agronomic purposes by controlled spreading on farm land (Giuffrida, 2010) and, consequently, this water is excluded from being under the waste category. In Portugal, Law No. 626/2000 sets the maximum limit for land application of OMWW for agricultural purposes at 80 m^3 ha^{-1} yr^{-1} (Koutsos *et al.*, 2018). No specific regulations are set by Greece, however, olive mills' owners are requested to submit an environmental impact assessment study for the produced wastewater (Galanakis, cited in Koutsos *et al.*, 2018) and

Table 2. Reported OMWW treatment efficiency for different technologies and estimated operation costs.

Reported OMWW treatment efficiency for different technologies					
Process	COD removal eff. (%)	Phenols removal eff. (%)	Ref.	Operating cost €/m^3	Ref.
Membrane (with pre-treatment	98	98 (does not comply with demanded regulations for disposal to public sewer network)	Paraskeva *et al.* (2007)	32	Paraskeva *et al.*, as cited in Gebreyohannes *et al.* (2016)
Coagulation/ flocculation using lime	57	63	Vuppala *et al.* (2019)	0.52	Vuppala *et al.* (2019)
Electro-coagulation	84[1]		1 Abou-Taleb *et al.* (2018)	23.4[a]	Haksevenler & Alaton (2014)
	38[2]	60[2]	2 Neffa *et al.* (2010)		
		92	Jalo *et al.* (2018)		
	43	21	Haksevenler & Alaton (2014)		
Aerobic treatment (activated sludge system)		76[3]	3 El-Hajjouji *et al.* (2014)	8.8	Beccari *et al.*, as cited in Zagklis *et al.* (2013)
	95[4]	93[4]	4 El-Moussaoui *et al.* (2018)		
Anaerobic digestion	19–97[5] depending on the technology		5 Gunay & Karadag (2015)	5.9	Beccari *et al.*, as cited in Paraskeva *et al.* (2012)
	80[6]	85[6]	6 Enaime *et al.* (2019)		
Electrolysis	60	63	Bouhssine *et al.* (2013)	36–45[b]	Gotsi *et al.* (2005)
Fenton	18	83	Amor *et al.* (2015)	10.8[a]	Haksevenler & Alaton (2014)
Photo-Fenton	80	88	Ahmed *et al.* (2011)	1.4[c]	Michael *et al.* (2014)
Ozonation	12	80	Martins *et al.* (2015)	4.4[d]	Paraskeva *et al.* (2012)

[a] Calculated based on provided data.

[b] Calculated based on provided cost (€/kg$\mathrm{COD}_{\mathrm{removed}}$) and assuming COD concentration of 100 g/L.

[c] OMWW is pretreated using coagulation flocculation technology, effluent is diluted, treatment plant is operating over 365 days, and costs are calculated assuming the treatment plant would serve a cluster of six olive mills.

[d] Calculated assuming removal efficiency of 44% and $\mathrm{COD}_{\mathrm{infl}}$ of 3.74 g/l.

each district is responsible for adopting proper management options. Furthermore, no limits are set for the allowable rate of OMWW application on agricultural land and the law only refers to water quality standards for the reuse of treated effluents (Koutsos *et al.*, 2018).

Apparently, three main related topics should be brought into national discourse regarding existing regulations: first, shall OMWW continue to be categorized as waste, or can it simply be considered as an agricultural by-product; second, can OMWW be used on agricultural land without treatment and what would be the acceptable application rate; third, and in case raw OMWW land application is not an option, would partial treatment followed by agricultural reuse be accepted and what would be the acceptable limits for the applied partially treated OMWW? In fact, the first topic is most critical since any called revision for effluent limits will be difficult without considering all other types of industrial wastewaters since JS 202/2007 is generic and covers all types regardless of the source.

Bottlenecks related to OMWW current management practice: shipping and disposal

OMWW is generally shipped to centralized storage ponds. Three locations are allocated by the government for northern, middle, and southern governorates, respectively. Each olive mill is requested to have a sealed concrete storage tank, while tankers are utilized to ship OMWW to the nearest designated site. Olive mill owners are obliged to go through the modus operandi shown in Figure 2 in order to guarantee a controlled process including OMWW proper disposal. Prior to the milling season, every mill is requested to get a yearly license from the Ministry of Local Administration to commence operation. Access to storage ponds' site needs the approval of the joint services council that regulates municipal services in the area where the mill is located. Fees are defined for each production line in the mill and account for 424 €, which is equivalent to around 0.62 €/m^3 of disposed OMWW. Accordingly, the mill owner receives a certain number of coupons that allow access to the designated storage ponds' site and to discharge OMWW. Additionally, the olive mill owner has to get a license from the

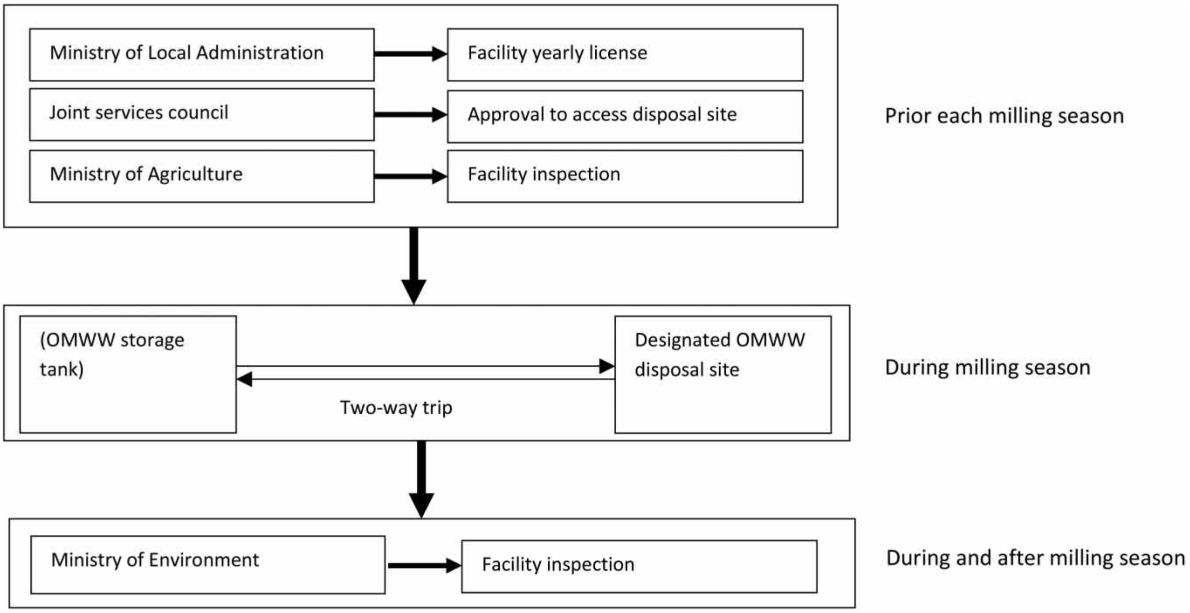

Fig. 2. Current control protocol for OMWW disposal.

Ministry of Agriculture – after conducting a field inspection to validate readiness of the mill including OMWW storage tanks – to commence milling.

OMWW is transported during the milling season by private tankers at a cost ranging from 3.5 to 4.6 €/m^3 per trip. On each trip, the olive mill owner hands one coupon with three copies to the driver; one copy has to be stamped by the authorities at the disposal site and returned back to the mill owner, while one copy is kept for records at the disposal site, and the last copy is left with the tanker driver. The driver is only paid after the stamped copy is returned back to the mill owner. As an additional precaution, the Ministry of Environment enforced an electronic tracking system for all tankers to prevent random dumping of wastewater. The Ministry also has the right to access olive mills and check for the stamped coupons. Despite all the control measures, the illegal disposal of OMWW is still practiced due to weak enforcement of penalties. Moreover, the absence of a representative body for the tanker owners complicates the authorities' role in communicating with this group to arrive at a certain agreement. In any case, shipping distance is apparently a key factor, determining whether the tanker owner is willing to arrive at the allocated disposal site or would discharge randomly to the environment.

When it comes to disposal site management, the Joint Services Councils are running the storage pond sites in the absence of clear legislation that defines the mandate of councils for such execution. The councils are currently receiving OMWW at the same locations of solid waste landfills by apportioning special areas for liquid waste. Accordingly, some drawbacks still exist at disposal sites, including lack of proper lining for the ponds and high potential for groundwater pollution. Moreover, the Joint Services Council has the right to cease admitting OMWW at any time if the allocated areas are needed for other purposes of higher priority. As a matter of fact, the debate has been around for a while regarding which entity should be responsible for liquid waste management. On one hand, the current practice might be considered as relatively inexpensive with a total cost ranging from 4.12 to 5.22 €/m^3 of OMWW when compared with other management alternatives that comprise wastewater treatment. However, and on the other hand, the practice is still insecure due to both the legislative gap that has to be closed and due to environmental issues. The lack of legal cover for the Joint Services Councils as the agency responsible for managing disposal sites discouraged the establishment of a decentralized management system that would allow better control of OMWW shipping.

Recommended actions and future perspectives

Recommended improvement actions would necessitate revisions for the legislative framework of OMWW management including category classification (e.g., wastewater, processing water, etc.), technical standards, and reuse options, particularly those related to raw OMWW agricultural use. The framework might be flexible in order to allow for the adoption of different management alternatives depending on socioeconomic considerations and technical aspects related to the selected option. For instance, agricultural land application of raw OMWW might be a good alternative in southern governorates where the groundwater table is low and contamination risks are very limited. However, the same option might not be considered a good solution in the northern governorates where the groundwater table is high. Moreover, impacts of OMWW agricultural land application on soil and plants should be known and acceptable. In fact, some studies conducted in Jordan have shown that no negative impacts were observed in soil or plants irrigated with OMMW. For example, it was shown that the application rate of 100 m^3/ha improved soil fertility and olive (*Olea europaea*, L.) orchard performance after three consecutive years of application (Ayoub *et al*., 2014). Application rate of 120 m^3 OMWW/ha had also resulted in increased soil organic matter and nutrient contents when applied in barley fields and had significantly increased plants' yield (Mohawesh *et al*., 2020). It is worth noting that traditional disposal of OMWW on soil has been so far the most commonly adopted solution in Italy despite the fact that such practice may result in groundwater contamination and deteriorate soil quality if not well managed (Chiavola *et al*., 2014). However, if well managed, OMWW might be considered as a low-cost fertilizer due to its high content of macronutrients that increase soil fertility and improve plant performance (Federici *et al*., 2009; Magdich *et al*., 2012; Tosi *et al*., 2013). Two main factors are critical to ensure efficacious OMWW land application; first, application rates are legislated based on evidence of retaining either no impact or a national acceptable environmental impact; second, a modus operandi which ensures a controlled process by the relevant authorities is established. In all cases, socioeconomic factors shall be considered since they might be critical to the success of such alternative. Accordingly, optimal local-level standards might be a good option to consider while establishing a revised legislation for each governorate (Lavee, 2013).

Notwithstanding the importance of raw OMWW agricultural land application, it is critical for a water-scarce country like Jordan to consider reuse of treated OMWW for agricultural production. However, this can only be done if more lenient standards are established. The standards shall take into consideration technological advances coupled with the fate of different contaminants in soils receiving treated OMWW. Partial treatment might be sufficient if pollutants are degraded when applied to the soil. The main potential advantages of this option are less malodors of treated wastewater, better social acceptance, and economic feasibility of the treatment technology.

Concerning the required control of OMWW shipping, capitalization on decentralized evaporation ponds might provide a good solution as this would encourage tanker owners to arrive at the designated destinations assigned by the authorities. Notwithstanding that *in situ* evaporation ponds might be a practical solution, large areas are required (Garcia & Hodaifa, 2017), which render this management alternative not feasible when land prices are high or land availability is limited. Land prices might be a considerable cost element in some regions of the middle and northern governorates in Jordan except if state-owned land is available. In any case, it should be noted that complete evaporation is not obtained even in areas with extremely high sunshine due to the oil layer present at the surface, which reduces evaporation rate and requires special management (Kelessidis & Christoforou, 2014; Koutsos *et al*., 2018). Furthermore, environmental nuisances (e.g., mosquitoes and odors), particularly during summer might present a challenge that needs to be addressed (Kelessidis & Christoforou, 2014). Despite these challenges, decentralized evaporation ponds might still be the most economic feasible option for OMWW management in case there is a consensus on discouraging agricultural reuse and keeping the current standards. A management alternative comprising decentralized evaporation ponds is not uncommon and has been adopted by many countries. In Spain, for instance, OMWW is discharged into 1,000 evaporation ponds, which were constructed to allow evaporation during summer (Garcia & Hodaifa, 2017; Koutsos *et al*., 2018). It should be noted that there is a total of 1,748 olive mills (IOC, cited in Garcia & Hodaifa, 2017) in Spain with more than 90% of the mills operating using the two-phase system (Kapellakis *et al*., 2008). *In situ* evaporation ponds are also the most common practice in Greece, Tunisia, and Portugal (Gargouri *et al*., 2013; Kelessidis & Christoforou, 2014; Esteves *et al*., 2019).

On the other hand, continuing the current management practice would also be an option provided that some improvements are considered: first, emphasizing the application of the penalties stipulated in the event of violation by tanker owners; second, assign the Joint Services Council as the body legally responsible for managing the liquid waste (in this case OMWW) in order to allocate resources. In this regard, a public–private partnership model might overcome lack of resources at the Joint Services Council; however, higher costs are expected for rehabilitating existing sites and for proper operation of evaporation ponds and sediment management.

Finally, and in point of fact, improved OMWW management is highly demanded for Jordan in view of the annual growing business and country obligations to meet targets 6.3 and 6.6 of the SDG6 on sustainable management of water and sanitation. Target 6.3 aims at – among others – halving the proportion of untreated wastewater and substantially increase recycling, while target 6.6 aims at protecting and restoring water-related ecosystems including aquifers and lakes. In this regard, recycling of valuable nutrients and organic matter found in OMWW by agricultural land application would be a feasible solution, particularly in the southern governorates. Moreover, better control on OMWW shipping would necessarily mean that progress has been made to meet target 6.6. Improvement of legislation is demanded in which responsibilities are well established and technical standards possess a wider scope. The main critical issue related to responsibility that needs urgent action – as mentioned earlier – is defining the authority that is responsible for managing disposal sites. Moreover, room should remain open within the standards' scope for different options, provided that allowable land application rates are established based on adequate scientific research.

A methodological approach shall differentiate the three categories of enabling environment, management instruments, and institutional roles. In this regard, sustainable water management that addresses water security, resource conservation, and resource recovery has to be considered. For instance, the high market price and great demand of antioxidants in cosmetic, pharmaceutical, and food industries encourage recovery of antioxidants such as hydroxytyrosol and tyrosol from OMWW (Kalogerakis *et al.*, 2013; Bassani *et al.*, 2016; Galanakis *et al.*, 2018). Additionally, organic fertilizer with 57% organic carbon content and N, P, and K contents of 3.5%, 1%, and 6.5%, respectively, can be produced by composting of OMWW following a solar drying step (Galliou *et al.*, 2018). Valorization of OMWW may also include biopolymers and bioenergy production (Mouzakitis *et al.*, 2017). Better involvement of the private sector may pilot OMWW valorization; however, an enabling environment must exist in which such practice is allowed by regulation and the know-how is accessible or transferred to the private sector.

Conclusions

Current Jordanian legislation discourages OMWW from being used for agricultural production, from discharging to wadis or disposing at public sewerage networks due to the very strict unattainable effluent quality limits. Existing instructions issued by the Ministry of Agriculture only allow olive mills to dispose of OMWW in centralized evaporation ponds that are operated by governmental bodies. OMWW shipping to disposal sites is well monitored, however, enforcement of penalties in the case of violations still needs improvement. Moreover, the governmental bodies (Joint Services Councils) are running the disposal sites in the absence of clear legislation that defines the mandate of councils for such execution. The existing legislative gap is considered critical to the sustainability of OMWW management and must be urgently addressed. While doing so, other management alternatives need to be considered, including OMWW valorization, OMWW land application, and capitalizing on decentralized disposal sites. This will require a complete review of the current legislative framework to allow agricultural use, decentralized management, identification of authorities responsible for legally managing disposal sites, and private sector participation.

Data availability statement

All relevant data are included in the paper or its Supplementary Information.

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